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# THE BRADLEY DEPARTMENT OF ELECTRICAL ENGINEERING

## FINAL REPORT

# "DESIGN AND CONSTRUCTION OF A PROTOTYPE ACTS PROPAGATION TERMINAL"

by

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# **Design and Construction of a Prototype ACTS Propagation Terminal**

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# Chapter 1. INTRODUCTION

## 1.1. Background

The Advanced Communication Technology Satellite (ACTS) systems has, in addition to sophisticated 20/30 GHz communications packages, 20/30 GHz propagation signals. The 20/30 GHz satellite communications band is as yet unused. It offers new spectrum space and the possibility of very small aperture terminal (VSAT) use. One major technical area that must be fully explored before operation deployment is that of propagation. Rain and atmospheric scintillation cause deep amplitude fluctuations in the 20/30 band. Systems must be designed carefully to mitigate impact on communications. This, in turn, requires accurate characterization of the propagation effects. ACTS offers a platform to perform such experimental studies.

Virginia Tech has designed and constructed a prototype of the ACTS Propagation Terminals (APT). The prototype APT was designed to facilitate the follow-on APT production phase. The production terminals will be deployed at seven sites funded by NASA to perform ACTS propagation experiments. A common hardware and software set reduces total costs, reduces the time individual experimenters must devote to experiment preparation, and provides a universal data collection standard.

The prototype phase is extremely important. It establishes the technical performance levels for the APTs. Considerable extra time was spent in this phase to reduce costs and production problems. This report documents the prototype terminal.

The APT has evolved through several stages. The first stage was the Olympus experiment at Virginia Tech. Receivers were designed and constructed to receive the three (12.5, 20, and 30 GHz) Olympus spacecraft beacons. Much of the technology used in these receivers carried over to the ACTS program. The use of a small antenna with a shared beacon/total power radiometer RF front end proved out very well when the enclosure temperature is carefully controlled. Data collection hardware and software carried over directly to ACTS. The Olympus beacon receiver is an analog FLL receiver, whereas the ACTS receiver is fully digital. The digital receiver evolved from thorough study and simulation, one pre-prototype hardware phase, and two prototype hardware implementations. There are other important improvements of the ACTS terminal over the Olympus terminal. The APT uses nearly all coaxial cable in the RF front end instead of waveguide to reduce size, assembly difficulties, and component costs. A complete downconverter block in each of the ACTS RF channels replaces discrete components in the Olympus front end. This state-of-the-art approach offers simplicity and reliability. The first IF frequency of the APT is 70 MHz compared to 1020 MHz for Olympus. Finally, a very sophisticated and expensive local oscillator

subsystem was used in Olympus; the ACTS LO subsystem is a simple multiplier chain.

## 1.2. Specifications for ACTS Propagation Terminals

The specifications of the ACTS spacecraft are given in Table 1-1. The receiving terminals, of course, must be carefully designed to be compatible with ACTS beacons.

A set of desired performance characteristics were drawn up through a series of NASA/JPL sponsored meetings that involved the propagation research community. These performance characteristics are listed in Table 1-2. Stated simply the goal of the APT development program is "To have standard hardware and software for ACTS propagation measurements at 20 and 27.5 GHz, while leaving flexibility for variations in individual experiments."

## 1.3. Progress Summary

The launch schedule for the ACTS spacecraft did not leave sufficient time for completion of the prototype APT prior to initiation of the APT production phase. In fact, the approach used was to construct and test all subassemblies of the terminal with special emphasis on the technically challenging portions. These include the RF front end that uses a state-of-the-art downconverter which integrates a low noise amplifier, mixer, post amplifier, filter, and local oscillator port frequency doubler into a single small package. In addition, we developed a new digital receiver that uses the latest DSP technology. Both of these subassemblies were thoroughly tested.

The highest risk technology in the APT program was the digital receiver. Several candidate algorithms and DSP chips were investigated early on, primarily under JPL sponsorship. A receiver was constructed based on Texas Instruments chip. [1] The final prototype digital receiver was one based on an Analog Devices chip. The design and test results are documented in a report [2] prepared for this grant.

A Primary Design Review (PDR) was conducted May 30, 1991, and a Critical Design Review was held July 7, 1992.

Final complete documentation of the APTs will appear in the form of three reports: a hardware description report, a report on the data collection code (ACTSVIEW), and a report on the preprocessing code.

Table 1-1

**ACTS Spacecraft Specifications**

Projected launch: Summer 1993: Launch vehicle: STS-51
Orbit slot: 100°W

<u>20 Beacon</u>

- Frequencies:
  - 20.185 GHz (vertical) primary, with 20.195 GHz (horizontal) as a backup.
- EIRP toward Blacksburg: 17.5 dBW including modulation loss
- Frequency stability (measured):
  - Primary (20.185): 10 kHz
  - Backup (20.195): 36 kHz
- Phase noise: -53 dBC/Hz at 50 Hz offset (measured)

<u>27.5 Beacon</u>

- Frequency: 27.505 GHz
- EIRP toward Blacksburg: 16.5 dBW
- Frequency stability (measured):
  - Primary (20.185): 102 kHz
  - Backup (20.195): 255 kHz
- Phase noise: -51 dBC/Hz at 50 Hz offset (measured)

Table 1-2

**User Community APT Performance Goals**

- Dynamic range: 25 dB
- Accuracy: 0.5 dB (0.1 dB resolution)
- Sample rate: 1 Hz or better
- HBR receive: no capability
- Radiometer
  - Absolute temperature: 1 K
  - Resolution: 0.2 K in 10 s
- Weather measurements (1 to 10 min. for temperature and humidity)
  - Point rain rate at terminal
  - Atmospheric temperature near earth
  - Humidity near earth
  - Ambient temperature of sensitive hardware
- Time: UT accurate to ± 2 s

## Chapter 2. SYSTEM DESCRIPTION

The physical diagram for the complete terminal package is shown in Fig. 2-1 as it appears in its normal operational configuration. There are five physical units: the antenna; the RF enclosure which contains all RF front end and downconversion with output at 70 MHz; the receiver enclosure which houses the radiometer chain, the beacon IF and digital receiver, and the data acquisition and collection system (DACS); the weather instrumentation; and the indoor equipment consisting of a computer, cassette tape unit, and a UPS (uninterruptable power supply).

The electrical block diagram of the APT is shown in Fig. 2-2. This section provides a brief overview of the complete terminal. The remainder of the chapter gives details on each subsystem. The APT consists of two complete, nearly identical 20.2 and 27.5 GHz channels each with beacon and radiometer receivers. Table 2-1 gives a summary of the performance which applies to either channel. Table 2-2 lists each component in Fig. 2-2 and subsequent block diagrams by identifying symbols.

Both signal frequencies (20.2 and 27.5 GHz) are received by 1.2-m offset parabolic reflector antenna. The 27.5 GHz signal is vertically polarized, while the polarization of the 20 GHz signal can be vertical or horizontal. A special OMT/Diplexer unit was constructed in-house to separate polarizations and frequencies. There is a primary unit and a full-replacement back-up unit for the 20.2 horizontal polarization back-up frequency. Each signal (20 and 27.5) then passes through a coaxial switch, and a downconverter block. The switch allows for the injection of excess noise for the purpose of radiometric calibration, and the downconverter block changes the RF signal to an IF frequency of 70 MHz. The signals are passed to the IF system for further processing.

In the Receiver enclosure the 70 MHz IF signal from the output of the RF system is first amplified and then split into two portions, one portion going to the radiometer and the other to a mixer. The mixer downconverts the 70 MHz to a 5 MHz signal which is subsequently filtered, amplified and sent to the digital receiver.

The radiometers are of total power type. They monitor the sky noise in a 50 MHz bandwidth about the beacon frequency. The radiometer consists of an attenuator for level adjustment, a two-stage amplifier, a square-law detector to convert the noise into a DC signal, and a DC amplifier. The 50 MHz bandwidth is set by a filter in the RF downconverter module. Automatic calibration of radiometer is achieved by injection of excess noise by means of noise diode which is housed in the RF enclosure.

Final processing occurs in the digital receiver. A digital receiver was chosen for several reasons. First, the ACTS signal

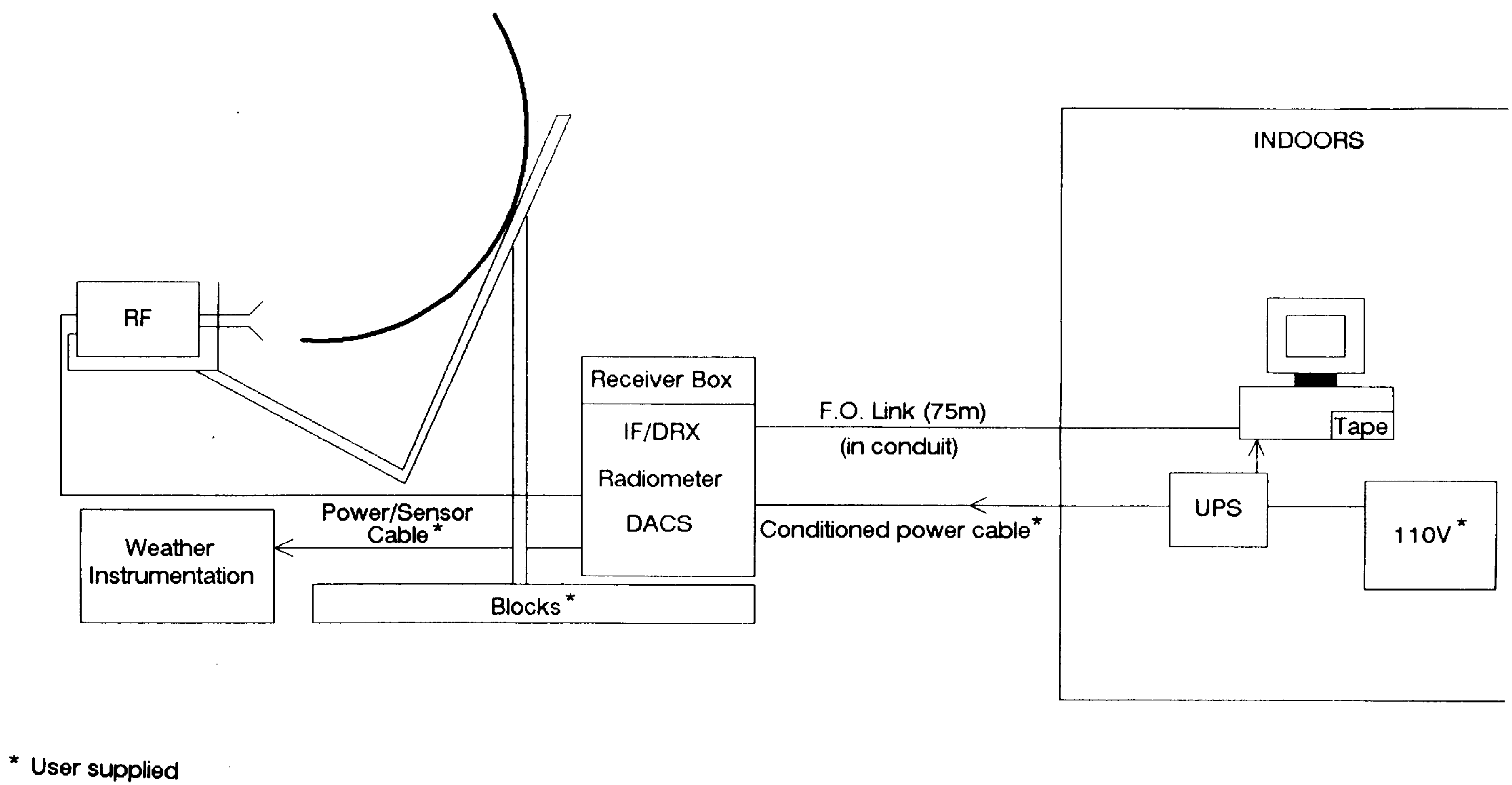



**Figure 2-1.** Physical diagram of the ACTS Propagation Terminal in its operational configuration.

Table 2-1

**The APT Performance Summary**

Configuration

The terminals will use a single antenna with frequency separation followed by separate 20 GHz and 27.5 GHz receivers. Co-polarized attenuation and scintillations at these frequencies are to be measured. There are provisions for a field change from 20V to 20H reception. Radiometers are included to remote baseline fluctuations.

Subassemblies
RF
    1.2 meter offset reflector
    LNAs - included
    Calibration methods:
        Inject test signal through feedhorn
        Remotely controllable IF attenuator
LOs: First LO type: Crystal controlled multiplier chain
IF: Input Frequency: 70 MHz (beacon and radiometer)
    Provisions for changing between 20V and 20H frequencies: change F4 to 60 MHz
    Output Frequency: 455 kHz

Subsystems
Radiometer
    Type: Total power
    Bandwidth: 50 MHz (image adds another 50 MHz)
    Detectable temperature: ± 1 K
    Calibration methods: noise diode and ambient load
        manual hot/cold loads to antenna
Beacon Receiver - Digital Receiver
    Input: 455 kHz
    A/D precision: 12 bit
    Output: Power and status in digital (32-bit) form
    Frequency drift tracking: ±152 kHz
    Bandwidth: 20 Hz
    Resolution: 0.01 dB
    Accuracy: ±0.1 dB
    Minimum C/N in 20 Hz bandwidth for acquisition: 10 dB
    Minimum C/N in 20 Hz bandwidth for tracking: 5 dB
    Reacquire time for loss-of-signal: under 5 s
    Acquisition time from cold start: under 30 s
Data Collection
    PC/AT based
    Sample rate: 1 Hz
    Data storage: 120 Mb tape (1.5 Mb/day of data)
    Weather ports: pressure, humidity, wind speed, wind direction, two rain gauges
    Modem: 2400 baud
    No downtime to store data to tape
    WWV-based clock system
    System monitors: power failure, receiver lock, PLO, outside temperature, RF encl. temperature, IF encl. temperature, spare

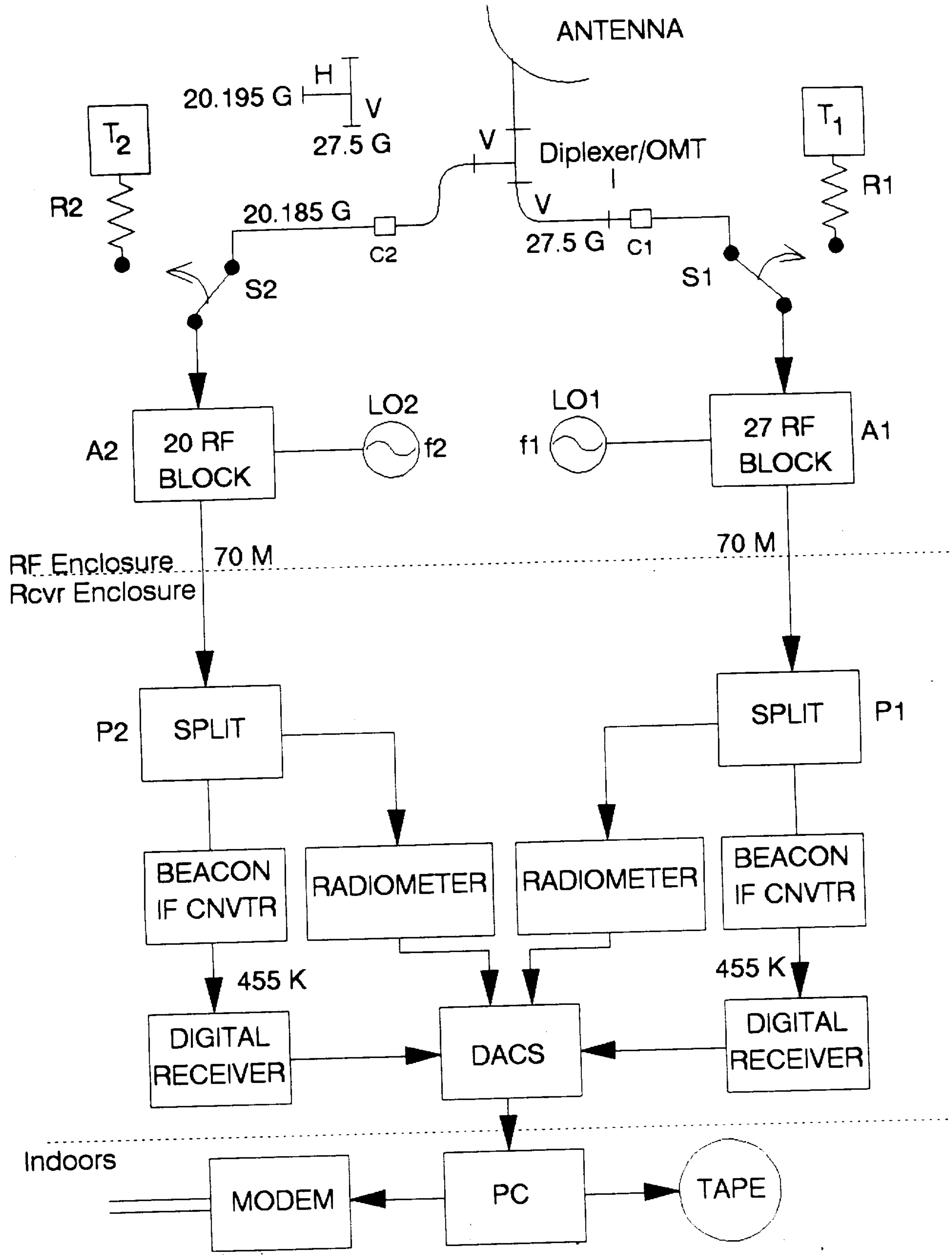



**Figure 2-2.** Electrical block diagram of the ACTS propagation terminal.

Table 2-2

**List of the APT Major Components**

$S_1$ - Electromechanical coaxial switch
$S_2$ - Electromechanical coaxial switch

$R_1$ - Fixed attenuator, 20 dB, coaxial
$R_2$ - Fixed attenuator, 20 dB, coaxial

I - Diplexer, fabricated in-house; 2 units, one for backup frequency on 20 GHz

$T_1$ - Noise diode
$T_2$ - Noise diode

$C_1$ - Waveguide to coax transition WR28 to K(M)
$C_2$ - Waveguide to coax transition WR42 to K(M)

$A_1$ - 27 RF downconverter block
$A_2$ - 20 RF downconverter block

$M_1$ - Mixer internal to 27 RF downconverter block
$M_2$ - Mixer internal to 20 RF downconverter block

$F_1$, $F_2$ - Filter, SAW, 70 MHz, 50 MHz BW, internal to RF downconverter blocks

$LO_1$ - Local oscillator, stable OCXO
$f_1$ = 27.505 GHz - 70 MHz = 27.435 GHz
$LO_2$ - Local oscillator, stable OCXO
$f_2$ = 20.185 GHz + 70 MHz = 20.255 GHz
(IF will be 60 MHz if 20.195 is active)

$P_1$, $P_2$ - Power divider, 3 dB
$A_3$, $A_4$ - Amplifiers, 55 to 85 MHz
$F_3$, $F_4$ - Filter, 70 M, 2.5 MHz BW
(Extra $F_4$ filter for backup with 60 MHz center freq.)
$R_3$, $R_4$ - Attenuator - programmable step, 0 - 20 dB, 1 dB steps
$A_5$, $A_6$ - Amplifier, 55 to 85 MHz
$M_3$, $M_4$ - Mixer, 5 MHz output

$LO_3$, $LO_4$ - Local oscillator, SMA connectors
$f_3$, $f_4$ = 65.0 MHz
$F_5$, $F_6$ - Filter, 5 MHz, 300 kHz BW
$M_5$, $M_6$ - Mixer, 455 kHz output
$F_7$, $F_8$ - Filter, 455 kHz, 180 kHz or 10 kHz BW switchable
$R_5$, $R_6$ - Attenuator - programmable step, 0 - 20 dB, 1 dB
$A_7$, $A_8$, $A_9$, $A_{10}$ - Amplifier, 70 MHz
$D_1$, $D_2$ - Detector diode
$A_{11}$, $A_{12}$ - Amplifier (DC)
$F_9$, $F_{10}$ - RC filter
$A_{13}$, $A_{14}$ - Operational amplifier

spectrum at 20 GHz contains many unwanted components. Analog receiver design and operation to ensure no false signal lockups would be complicated. A "smart" digital receiver is better suited for this environment. Replication of the receiver for production units will be easier with a board and plug-in processing chip design approach. Recent chip developments make a digital receiver within reach. Finally, this development program is appropriate to the university research environment and adds to the technology development theme. The input frequency to the digital receiver was selected to be 455 kHz. This choice was driven by the fact that the A/D chips work up to 1 MHz. Thus for Nyquist sampling 500 kHz is the upper bound. A center frequency of 455 kHz allows the use of low cost, high performance filters commonly used in communications receivers.

# Chapter 3. PERFORMANCE RESULTS

In addition to standard bench tests, two system tests were performed on the beacon receiver using satellite signals. One used the Olympus satellite 20 GHz beacon and a second test was performed in Princeton, NJ, using the ACTS spacecraft while it was undergoing final ground testing. This chapter describes test results. The bench tests and measurements with Olympus are detailed in [2].

## 3.1. Results from Bench Tests

Accuracy and linearity tests were performed on the APT receiver by injecting a synthesized 455 kHz signal into the receiver's input using a Hewlett Packard HP3330B signal generator. As shown in the following sections, the receiver produces exceptionally accurate, linear signal power measurements over the +8 dBm to -35 dBm operating region. These results exceed the goals established by Virginia Tech and those defined by the ACTS Users' Community.

### 3.1.1. Power Measurement Accuracy

One hundred measurements were made to determine the accuracy of the APT receiver signal power measurement. The measurements were taken at signal levels from +10 dBm to -35 dBm (1 dBm increments). The standard deviation of the signal power measurements made at each signal level are presented in Table 3.1-1. The resolution of all APT receiver signal power measurements is 0.01 dB. This quantization is reflected in the data presented below. The data presented below indicates that the APT front end attenuator alters the signal level but does not significantly affect the system noise level.

The APT receiver was able to reliably identify the carrier signal at signal-to-noise ratios down to 10 dB in a 20 Hz bandwidth (23 dBHz in a 1 Hz bandwidth, 26 dB fade conditions on the APT system) in 2 seconds. Note the results of signal power measurement tests at levels greater than +8 dBm were not presented because the receiver saturates at +8 dBm due to the voltage gain of 4 in the analog-to-digital converter circuit. This voltage gain can be altered to provide a signal power measurement range suited to a specific application.

### 3.1.2. Receiver Linearity

Linearity tests were performed by injecting a synthesized 455 kHz signal into the receiver's input using an HP3330B signal generator. 100 signal power measurements were obtained at signal levels from +10 dBm to -35 dBm in 1 dBm increments. The geometric mean of the measurements taken at each signal power level are plotted versus their expected values in Fig. 3.1-1. It is evident

Table 3.1-1

**Standard deviations of APT receiver signal power measurements**

| Signal Level (dBm) | Standard Deviation (dBm) | | Signal Level (dBm) | Standard Deviation (dBm) |
|---|---|---|---|---|
| +10.00 | | | -13.00 | 0.0210 |
| +9.00 | | | -14.00 | 0.0212 |
| +8.00 | 0.0211 | | -15.00 | 0.0186 |
| +7.00 | 0.0194 | | -16.00 | 0.0219 |
| +6.00 | 0.0197 | | -17.00 | 0.0217 |
| +5.00 | 0.0184 | | -18.00 | 0.0196 |
| +4.00 | 0.0210 | | -19.00 | 0.0224 |
| +3.00 | 0.0200 | | -20.00 | 0.0196 |
| +2.00 | 0.0192 | | -21.00 | 0.0195 |
| +1.00 | 0.0216 | | -22.00 | 0.0201 |
| 0.00 | 0.0203 | | -23.00 | 0.0199 |
| -1.00 | 0.0188 | | -24.00 | 0.0202 |
| -2.00 | 0.0212 | | -25.00 | 0.0209 |
| -3.00 | 0.0189 | | -26.00 | 0.0238 |
| -4.00 | 0.0190 | | -27.00 | 0.0221 |
| -5.00 | 0.0192 | | -28.00 | 0.0201 |
| -6.00 | 0.0184 | | -29.00 | 0.0216 |
| -7.00 | 0.0217 | | -30.00 | 0.0207 |
| -8.00 | 0.0213 | | -31.00 | 0.0208 |
| -9.00 | 0.0189 | | -32.00 | 0.0217 |
| -10.00 | 0.0196 | | -33.00 | 0.0200 |
| -11.00 | 0.0212 | | -34.00 | 0.0204 |
| -12.00 | 0.0104 | | -35.00 | 0.0200 |

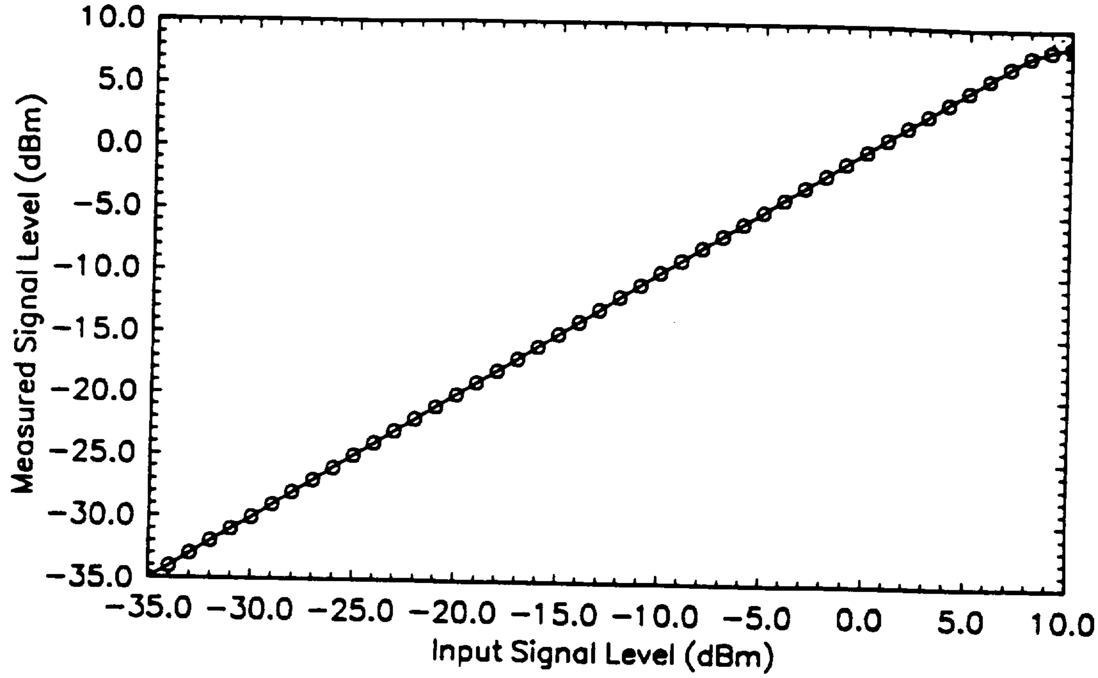



**Figure 3.1-1.** Plot of APT receiver's linearity curve. Each point represents the geometric mean of 100 signal power measurements.

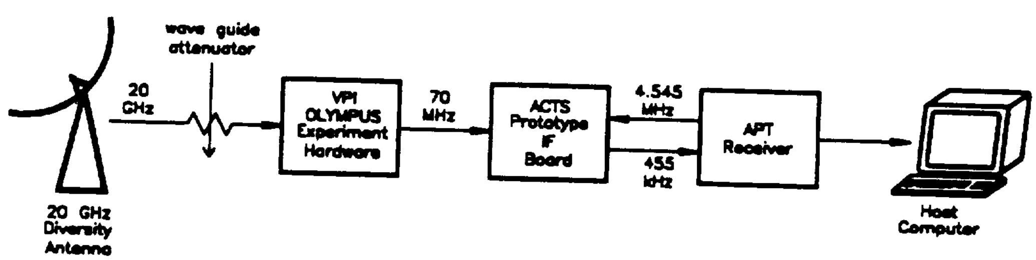



Figure 7-1. System used to test the APT receiver with the OLYMPUS 20 GHz beacon

**Figure 3.2-1.** Test setup using the Olympus 20 GHz beacon.

that the receiver's output is exceptionally linear over a +8 dBm to -35 dBm operating range.

### 3.2. Testing Using the Olympus 20 GHz Beacon

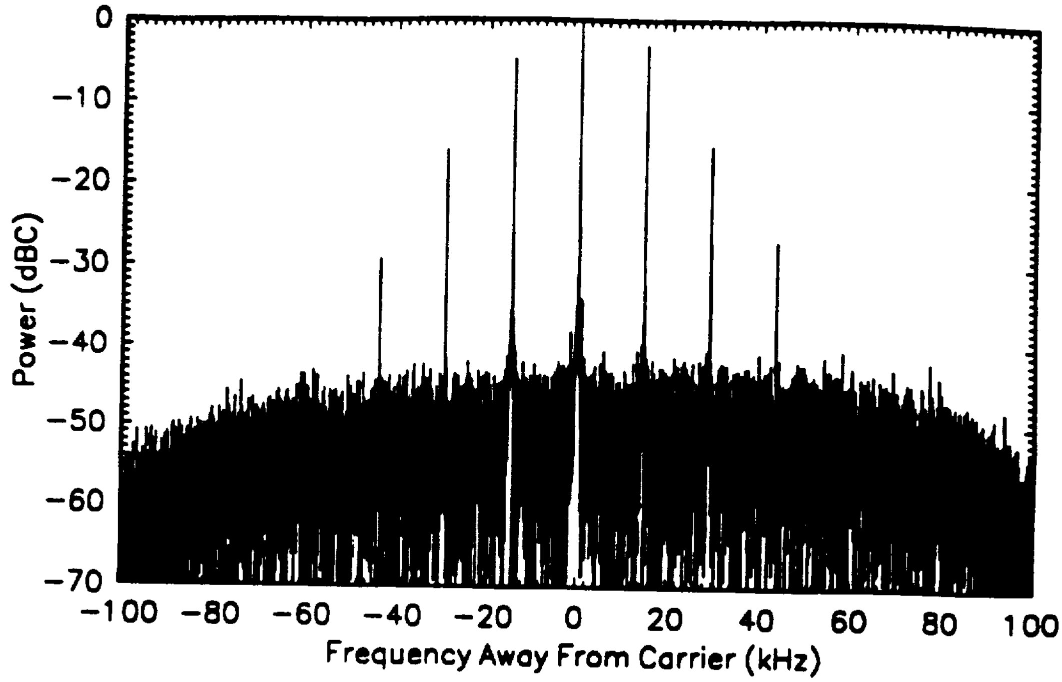
Virginia Tech has two complete 20 GHz (19.66 GHz) beacon receivers, one fixed and one portable. The portable one was available for testing. This permitted direct comparison of the performance using one Olympus receiver and a second Olympus signal which was fed to the ACTS IF and digital receiver chain as shown in Fig. 3.2-1.

Although the Olympus 20 GHz beacon is not modulated with telemetry information or ranging tones, spectral peaks representing the odd harmonics associated with square wave modulation appear in the Olympus 20 GHz beacon spectrum. The polarization of the Olympus 20 GHz beacon is switched at 933 Hz. The switching polarization appears as square wave modulation at the APT receiver input because the hardware which performs the 20 GHz to 455 kHz downconversion only accepts the co-polar signal. The resulting tones are much closer to the Olympus 20 GHz beacon than corresponding tones will be to the ACTS 20 GHz beacon. Hence the side tones on the Olympus 20 GHz beacon rigorously test the APT receiver carrier signal acquisition algorithm. The data demonstrate that the APT receiver will reliably acquire the ACTS beacon signal and will provide exceptionally accurate linear signal power measurements. The acquisition characteristic of the receiver was determined by repeatedly attempting to acquire the Olympus 20 GHz beacon at different signal-to-noise ratios. The test system used is shown in Fig. 3.2-1. The Olympus 20 GHz beacon signal is available at 70 MHz at the output of the Virginia Tech's Olympus experiment hardware. The 70 MHz signal was downconverted to 455 kHz by the prototype ACTS IF chain and input to the receiver. Different signal-to-noise ratios were generated by adjusting a waveguide attenuator in the front end of the Olympus experiment hardware. The primary component in the system noise level is thermal noise from the electronic components used to amplify, bandlimit and translate the 20 GHz signal down to 455 kHz. Sky noise contributions to the system noise level are very small. Therefore, adjusting the front end attenuator alters the signal level but does not significantly affect the system noise level.

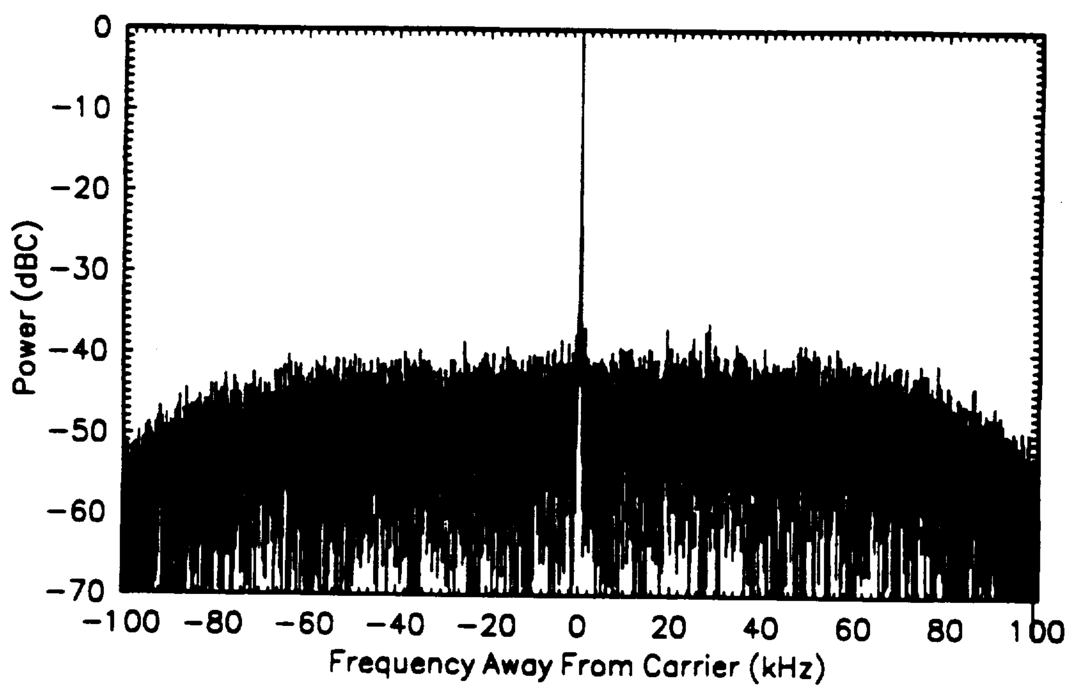
#### 3.2.1. Acquisition Tests

The APT was able to reliably identify the carrier at signal-to-noise ratios down to 10 dB in a 20 Hz bandwidth in 2 seconds.

Figure 3.2-2 shows sample spectra from the receiver. The switching side tones are evident.




(a) 32768 - point spectrum




(b) Expanded view of (a)

**Figure 3.2-2.** Spectra from the ACTS digital receiver using the Olympus satellite 20 GHz beacon which is on-off switched at 933 Hz.

### 3.2.2. Receiver Dynamic Range Tests

Dynamic range tests were conducted on the APT receiver using the Olympus 20 GHz beacon. In order to make accurate signal power measurements, the receiver must be able to distinguish the carrier signal from spurious noise spikes. To determine its ability to identify the carrier signal, the APT receiver calculates the variance of the difference between consecutive carrier frequency estimates. Tests show that the APT receiver is unable to reliably identify the carrier at signal-to-noie ratios below approximately 5 dB in a 20 Hz bandwidth (18 dBHz in a 1 Hz bandwidth, 31 dB fade conditions on the APT system).

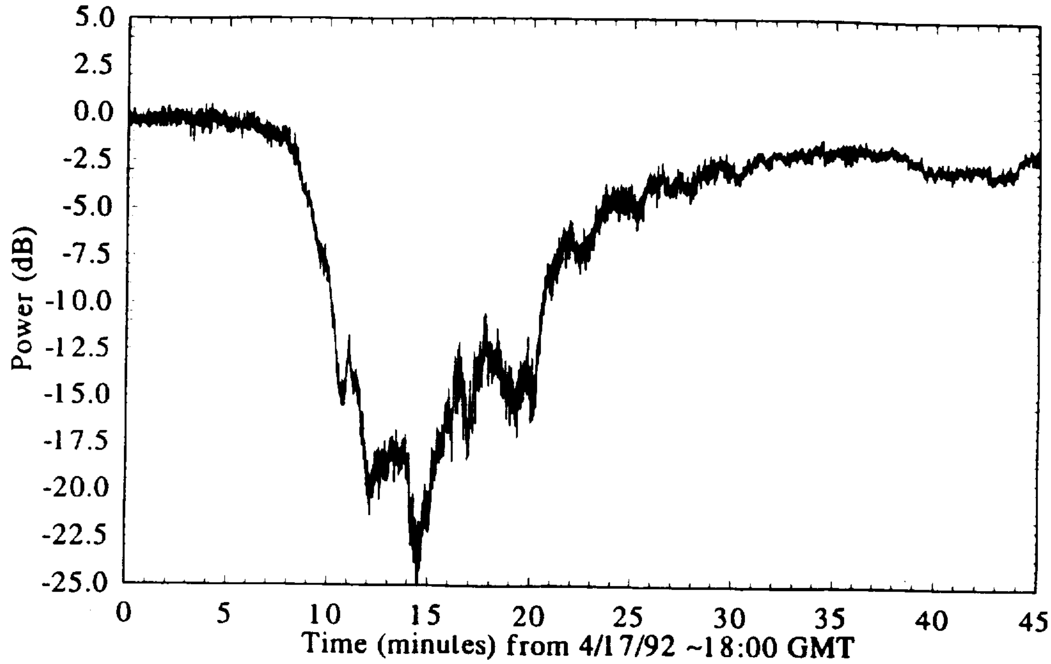
### 3.2.3. Rain Fade Tests

The test that most closely resembles ACTS operating conditions is that of a rain fade on a satellite beacon. A heavy rain event was monitored on the two Olympus 20 GHz beacon receivers, one using the Olympus analog system and the other using the ACTS IF/DRX (see Fig. 3.2-1). Figure 3.2-3 demonstrates virtually identical results for the fade.

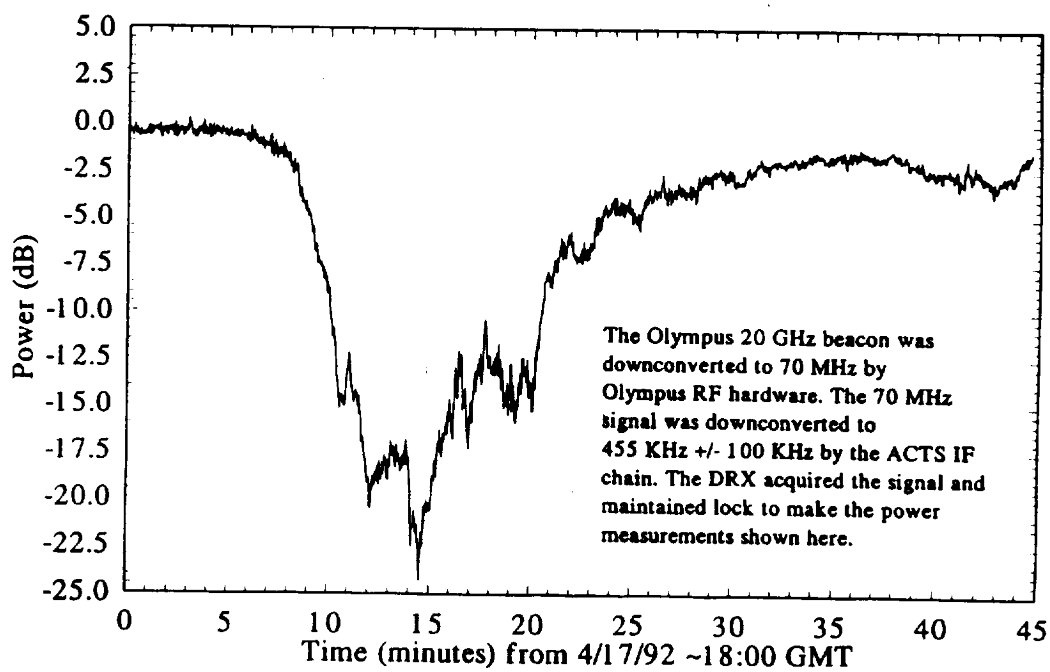
## 3.3. Tests With ACTS Spacecraft

In August 1992, the ACTS prototype receiver was transported to GE Astro-Space in Princeton, NJ, for two days of tests. The spacecraft beacons were turned on and cycled through various modulation modes.

The APT system performed very well. It acquired and tracked the 20 and 27 GHz ACTS beacons. Figure 3.3-1 shows sample spectra.

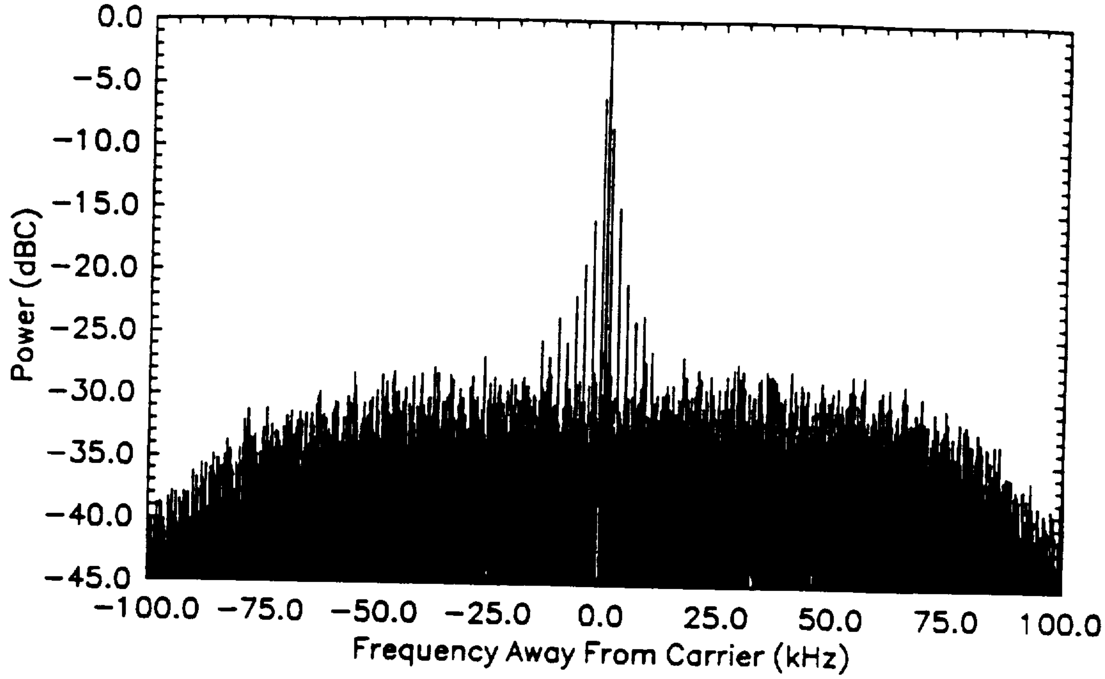



(a)

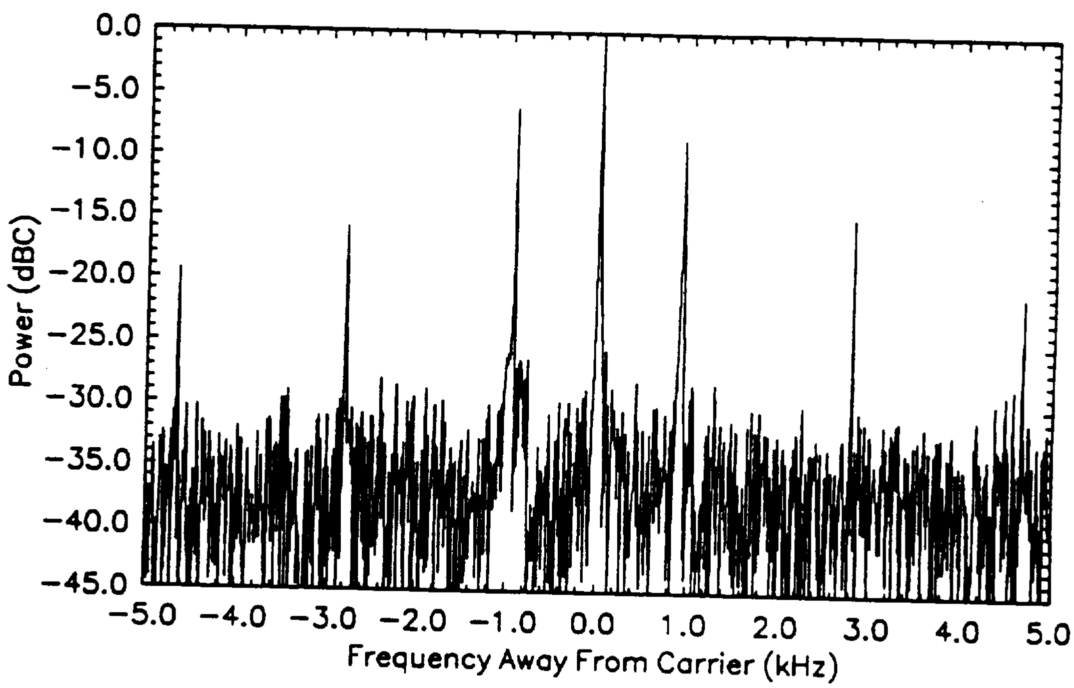



(b)

**Figure 3.2-3.** A rain event of 45 minutes duration on the Olympus 20 GHz beacon on April 1, 1992, received on the Olympus analog receiver (a) and ACTS digital receiver (b).




(a) 32,768 - point spectrum of the 20 GHz beacon in attitude monitor mode.




(b) 32,768 - point spectrum of the 27.5 GHz beacon.

**Figure 3.3-1.** Spectra taken with the APT prototype receiving system in August 1992 with the ACTS spacecraft in Princeton, NJ.

## Chapter 4. REFERENCES


1. Ginger Runyon, "Parallel Processor Architecture for a Digital Beacon Receiver," VPI & SU Report No. EESATCOM 90-6, M.S. Thesis, July 1990.

2. William R. Sylvester, Jr., "Theory, Design and Implementation of a Digital Receiver for the Advanced Communications Technology Satellite (ACTS) Beacons," VPI & SU Report No. EESATCOM 92-3, August 1992.